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**THE THRESHOLD OF THE STAPEDIUS REFLEX TO SELECTED
ACOUSTIC STIMULI IN NORMAL HUMAN EARS**

by

Lawrence J. Deutsch

Bureau of Medicine and Surgery, Navy Department
Research Work Unit MF12.524.004-9010D.01

Released by:

Gerald J. Duffner, CAPT MC USN
COMMANDING OFFICER
Naval Submarine Medical Center

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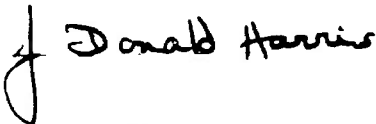
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SUBMARINE MEDICAL RESEARCH LABORATORY
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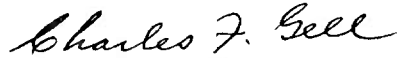
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Submitted by:



J. Donald Harris, Ph.D.
Head
Auditory Research Branch

Reviewed and Approved by:



Charles F. Gell, M.D., D.Sc.
Scientific Director
SubMedResLab

Reviewed and Approved by:



Joseph D. Bloom, CDR MC USN
Director
SubMedResLab

Approved and Released by:



Gerald J. Duffner, CAPT MC USN
Commanding Officer
Naval Submarine Medical Center

SUMMARY PAGE — REPORT No. 546

THE PROBLEM

To determine the feasibility of constructing a standard objective test for middle-ear muscle activity.

FINDINGS

A commercially-available acoustic impedance bridge, coupled to a microphone and a sound level recorder, provides a sensitive index to middle-ear muscle activity. Reliability and stability are high. The normative data provided herewith enhance the method as a usable tool for studies on the effects of submarine noises on hearing of a naval population.

APPLICATION

Material presented will be useful for otologists, audiologists, safety engineers, and others working in several phases of the Navy's Conservation of Hearing Program.

ADMINISTRATIVE INFORMATION

This investigation was conducted as a part of Bureau of Medicine and Surgery Research Work Unit MF12.524.004-9010D—Optimization of Auditory Performance in Submarines. This report is No. 13 on this Work Unit. It was approved for publication on 24 September 1968 and designated as Submarine Medical Research Laboratory Report No. 546.

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ABSTRACT

The threshold sound pressure levels for the middle-ear stapedius muscle reflex in response to white noise (constant spectrum level), and to pure tones and narrow bands of noise in the regions of 2 and 4 kilocycles per second, were studied with the Zwislocki acoustic impedance bridge and an objective recording method. Means and the shape of the distributions were provided. Mean thresholds for noise were as low as 62 decibels above audiometric threshold. Reliability and stability were high. It was concluded that the method could be used for a variety of purposes in audiometry, clinical audiology, and physiological acoustics; and for such purposes this paper provides normative data from 30 normal-hearing Submarine School candidates. There are a number of situations with which submarine medicine is concerned where a specific knowledge of the action of the middle ear muscles, such as provided almost solely by the method of this report, would be of value.

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THE THRESHOLD OF THE STAPEDIUS REFLEX TO SELECTED ACOUSTIC STIMULI IN NORMAL HUMAN EARS*

I. INTRODUCTION

A. The Middle Ear Muscles.

Hensen in 1878 first observed contraction of the middle ear muscles in dogs upon exposure to an intense acoustic stimulus (Wever and Lawrence¹). Metz² demonstrated that contraction of the stapedius muscle changes impedance measured at the tympanic membrane. The work of Metz led to numerous clinical and theoretical studies of the acoustic reflex in humans and animals. The extensive literature suggests that further study of the stapedius reflex may contribute significantly to more sophisticated clinical diagnosis of middle and inner ear conditions, as well as providing knowledge of the physiological function of the middle ear muscles (Jepsen³).

1. Anatomy, Physiology, and Nerve Supply.

The middle ear of man (and other mammals as well) contains two small muscles, the tensor tympani and the stapedius, the former first described by Eustachius in 1564, the latter by Varolius in 1591 (Wever and Lawrence¹).

The stapedius muscle is phylogenetically the older of the two muscles; it develops from the hyoid arch and can be recognized in 13.5-mm embryos. The tensor is developed from the first branchial arch and can be identified in 22-mm embryos (Jepsen³).

The tensor tympani originates in a slender canal that travels above the bony Eustachian tube and is separated from it by a very thin partition of bone and fibrous tissue. The tensor tendon runs from the muscle through a bony channel, makes a turn around a hook on the promontory called the cochleariform process, and enters the

middle ear cavity; it inserts on the medial side of the manubrium of the malleus. The bony channel acts as a pulley to change the direction of action from anterior to antero-medial (Kobrak⁴).

Mean length of the human stapedius is 6.3 mm, cross-section of 49 mm². The mean length of the human tensor tympani is 25 mm, cross section 5.85 mm² (Wever and Lawrence¹).

Contraction of the tensor tympani pulls inward and forward, at a right angle to the ossicular chain, causing movement of the tympanic membrane.

The stapedius muscle lies in a bony canal posterior to the middle ear cavity, adjacent to the canal of the facial nerve. The stapedius tendon leaves the canal through the pyramidal eminence and is inserted on the neck of the stapes.

The stapedius pulls in a posterior direction with reference to the main axis of the stapes; the tension applied by the stapedius is opposite in direction to the tensor.

The tensor tympani is supplied by the mandibular branch of the trigeminal (V cranial) nerve. The stapedius muscle is innervated by the facial (VII cranial) nerve.

Both muscles are difficult to visualize, even during surgery, because of their casings. Bekesy suggested that this type of structure prevented the muscles from vibrating laterally when sound passes through the ossicular chain, thereby preventing distortion and damping (Kobrak⁴, Jepsen³).

2. The Reflex Arc.

The contraction of the stapedius muscle to the presentation of a sound stimulus is considered to be a reflex arc. The afferent portion of the arc is the cochlear nerve; the crossover to the efferent neuron is thought to occur in the superior olivary complex. The efferent branch of the arc is the facial nerve which delivers the impulse to the stapedius muscle (Jepsen³). Luscher⁵ demonstrated

* Time spent in SMRL collecting data was supported by the Veterans Administration. Another draft was submitted to The City University of New York for the Ph.D.

that a stapedius muscle contraction could be elicited in animals in the form of a conditional reflex (Jepsen³).

As early as 1886 Pollack demonstrated that the acoustic reflex was bilateral in nature (Lilly⁶). In other words, sufficient acoustic stimulation of either ear will result in the presence of an acoustic reflex in both ears.

3. The Acoustic Reflex.

a. Methods of recording intratympanic muscle activity.

Some studies have used direct microscopic observation of the human tympanic cavity, either through traumatic perforations of the eardrum or during surgery.

A large number of animal and some human studies have used the electromyographic technique (recording of action potentials from the tympanic muscles.)

Tympanometric techniques have been used to measure changes in pressure in the external auditory canal. These changes in pressure are associated with small movements of the tympanic membrane that accompany contractions of the tympanic muscles. Møller⁷ warns, however, that small contractions of the stapedius may not produce measurable changes in air pressure.

Some studies have used changes in the cochlear microphonic level, which are due to contractions of the tympanic muscles, for middle ear muscle study (see Wever and Vernon⁸, Galambos and Ruppert⁹, and Simons¹⁰, among others.)

A method used extensively in the past 15 years is the measurement of changes in the acoustic impedance at the eardrum. With proper instrumentation, this method is relatively easy to perform, sensitive and reliable.

b. Response to Acoustic Stimulation.

Bockendale in 1880 noticed changes in eardrum tension upon presentations of an acoustic stimulus to dogs and cats; increase in tension seemed to be related to the loudness of the stimulus (Wever and Lawrence¹.)

In 1913 Mangold attributed a diminution of air pressure in the external canal associated with acoustic stimulation, to inward

movements of the eardrum (Wever and Lawrence¹.)

Luscher⁵ first observed stapedius contraction to acoustic stimulation in humans. He used microscopic observation through perforations in the tympanic membrane. This observation was confirmed by Potter¹¹.

Kato¹² observed stapedius movement in response to sound stimuli in cats and rabbits; the tensor tympani also contracted to acoustic stimulation but more intensity was required.

Lorente de No¹³ reported an acoustic tensor reflex in cats and rabbits. Lorente de No and Harris¹⁴ were able to observe, through direct microscopic observation, the contraction of both intratympanic muscles in decorticated rabbits; responses were elicited to stimuli in the 128 to 1686 c/s range.

Eliasson and Gisselsson¹⁵ recorded electromyographic responses in decerebrated cats from both middle ear muscles; the threshold of the tensor tympani was 30 db higher than the stapedius.

Wersall¹⁶ using a similar technique obtained myographic responses in anesthetized rabbits from both muscles when a 1-kc/s tone was presented.

Galambos⁹ measured an acoustic tensor reflex in unanesthetized cats.

Klockhoff¹⁷ notes that Kato¹² was unable to demonstrate an acoustic tensor reflex in monkeys, although contractions of the stapedius were observed.

Jepsen¹⁸ examined the acoustic reflex, by the impedance method, in seven patients with Bell's palsy, which is known to cause paralysis of the stapedius muscle. He was unable to demonstrate any acoustic reflex in these ears. He also studied two patients with tensor paralysis and was able to record changes in impedance in both of these ears upon the presentation of sufficient acoustic stimulation (Klockhoff¹⁷). Based on these data he concluded that in humans the acoustic reflex was in reality an acoustic stapedius reflex.

Klockhoff¹⁷ used the impedance method to examine 15 patients with unilateral facial palsy. All patients displayed an acoustic re-

flex on the contralateral side but none responded to a 1-kc/s pure tone at 120 db sound pressure level (SPL) on the side with the palsy.

Klockhoff also examined five ears with suspected ossicular discontinuity; the diagnosis was confirmed surgically following his examination. He was unable to demonstrate an acoustic reflex in these ears, using the impedance method. He felt this conclusively demonstrated that, in man, only the stapedius muscle contracts to acoustic stimulation.

Feldman¹⁹, using the Zwislocki acoustic bridge, studied several cases in which the stapedius muscle was inoperative due to pathological or postsurgical conditions. In each instance he was unable to observe an acoustic reflex. Feldman also examined five patients with sectioned tensor tympani muscles and was able to demonstrate a normal reflex in each case. He concluded that while using impedance monitoring, it had never been possible to document an acoustic tensor tympani response in man.

Kawata²⁰ observed movements in the slope of the manubrium in the human ear when stimulated by sound. Terkildsen²², while using tympanomanometry in man, recorded inward movements of the eardrum. He concluded that this must be due to contraction of the tensor tympani and suggested that the tensor response must be dominant over the concurrent stapedius responses.

Holst²³, et al recorded eardrum movements which they attributed to the tensor tympani, upon the presentation of an intense acoustic stimulus (127 db SPL at 500 c/s.) The authors accepted inward movements of the drum (a decrease in pressure) as evidence of a tensor response and outward movement of the drum (an increase in pressure) as probably indicative of a stapedius response. They also recorded biphasic movements which they attributed to a combined response of the two middle ear muscles. They concluded that the middle ear muscle reflex is a contraction of both muscles simultaneously; they noted that the threshold for stimulating the tensor is about 15 to 20 db higher if the stapedius has been sectioned.

It must be noted that the intensity of the stimuli used by these experimenters was so high that they may well have caused a gross startle reaction. The authors denied this possibility.

Djupestrand²⁴ studied the acoustic reflex during 125 surgical procedures; he used impedance measurements, electromyography, and direct microscopic inspection to collect data from both acoustic and non-acoustic stimulation. He concluded that pure-tone stimulation in the range 65-115 db above threshold (sensation level, SL) usually produced only a stapedius reflex. Tensor tympani muscle contractions could be obtained when the stimulus was unusually loud, especially if unexpected; the test subjects reacted to this type of stimulus by closing their eyes at the same time as contracting the tensor muscle. Djupestrand concluded that the tensor tympani contraction is part of the startle-related cochleo-palpebral reflex and can be expected at 115-140 db SPL.

This agrees with the opinion of Salmon and Starr²⁵ who recorded a tensor response electromyographically following the stapedius response at high intensities.

The tensor tympani thus might have an acoustic reflex, but if so it does not normally alter the impedance of the middle ear. Therefore, the reflex measured by an acoustic bridge may properly be called the stapedius reflex. Furthermore, it appears probable that any contraction of the tensor tympani to acoustic stimulation can be thought of as a part of the generalized startle response.

c. Response to Non-Acoustic Stimulation.

The majority of early reports of a non-acoustic middle ear muscle reflex stemmed from accidental tactile stimulation in or around the ear canal. This response to tactile stimulation was noted in animals by Lorente de No¹³, Wiggers²⁶, and Wersall¹⁶, among others. According to Jepsen³, Kato reported that the middle ear muscles contracted to a weak air current in the external canal.

Luscher⁵ occasionally noticed the contraction of the middle ear muscles in human subjects upon tactile stimulation of the

canal. Both Metz² and Jepsen³ (in Klockhoff¹⁷) were unable to demonstrate this. Klockhoff¹⁷ used a cutaneous electric shock in the ear canal to elicit a middle ear muscle reflex. He found, using an impedance technique, that the electric shock stimulated only the stapedius muscle. He demonstrated this with six subjects with unilateral facial palsy; he was able to elicit a response only on the ear contralateral to the paralysis. He noted that in normal ears the cutaneous muscle response is unilateral, in contrast to the bilateral acoustic stapedius response.

Djupestrand²⁴ repeated this phase of Klockhoff's work using direct observation and electromyography in addition to impedance measures. He also recorded no response of the tensor tympani to electric shock in the canal; however, he found the response of the stapedius to be bilateral to cutaneous stimulation in the canal.

Klockhoff¹⁷ demonstrated a non-acoustic tensor reflex to an orbital air jet. Using 18 ears in which a stapedius response had been precluded (ossicular discontinuities, stapedial fixations and sections, etc.), he recorded responses more intense and of shorter latency than the stapedius reflex. Klockhoff considered this response to be a part of the generalized startle response. He suggested that in normal ears both muscles would contract to such stimulation. Linden and Norland (in Lindstrom and Linden²⁷) confirmed this by direct observation during surgery.

Kjupestrand²⁴ showed contraction of the middle ear muscles during voluntary and reflex contraction of the peri-orbital muscles. He offers the following examples: coughing, laughing, yawning, touching the cornea, and touching the nasal mucosa.

In summary, it seems that all tympanic muscle responses to acoustic stimulation in humans at the sub-startle level can be attributed to the stapedius. The responses of the tensor tympani are probably related to the cochleo-palpebral reflex and are usually associated with very intense acoustic stimuli or other startle-inducing stimuli.

d. Threshold of the Stapedius Reflex.

Most of the early experiments employed experimental animals rather than

human ears. Lilly⁶ notes that there is no experimental evidence to suggest that the threshold of the stapedius reflex in man is even close to that of the cat.

Lorente de No and Harris¹⁴ visualized responses in rabbit; the threshold (in db re the normal human ear) of the stapedius was approximately 65 db at 500 c/s; the tensor had a threshold of 82 db for the same frequency. The threshold of the stapedius was 42 db at 1 and 58 db at 2 kc/s; the corresponding tensor tympani thresholds were 55 and 60 db respectively. The threshold for both muscles was approximately 45 db at 4 kc/s.

Eliasson and Gisselsson¹⁵ recorded responses from decorticated cats electromyographically and found the stapedius threshold to be 40 db; tensor tympani responses were recorded at 70 db, both values with reference to normal human hearing.

Wever and Vernon²⁸ found the threshold for the acoustic reflex in cat to lie between 80 and 100 db SPL.

Wersall¹⁶ studied the acoustic reflex threshold in 11 rabbits with electromyography. He found that the stapedius responded to a 1-kc/s tone at 96 db SPL, the tensor at 104 db SPL. He noted that in some rabbits the threshold for the stapedius and the tensor tympani were the same while in other rabbits the tensor reflex required as much as 22 db of additional stimulation.

Simmons²⁹ used a similar technique, and found the mean threshold in cat to a white noise stimulus to be about 50 db SPL. The difference between the thresholds of the two muscles was found to be no more than 10 db.

Lindsay, et al³⁰ found that the stapedius threshold in human ears varied from 65 to 85 db SL. Jepsen¹⁸ found impedance thresholds in the human of about 80 db SL (250 to 4000 c/s). Metz³¹ also found that human impedance thresholds varied at 70-90 db SL.

Jepsen³ determined the stapedius reflex threshold to be most sensitive to pure tones of 1-2 kc/s, approximately 75 db SL; the threshold for 250 c/s was 85 db SL, for 500 and 4000 c/s was 80 db SL. He also found that the threshold of the stapedius reflex

tends to decrease with age, especially at the higher frequencies. He attributed this decrease to recruitment.

Weiss, et al³² by tympanomanometry found thresholds (400-6400 c/s) to lie between 96 and 107 db SPL. They also noted that it required less intensity to stimulate the reflex at 800 to 3200 than it did at 400 or 6400 c/s. The thresholds are from tensor activity.

Lilly⁶ determined the stapedius reflex threshold to white noise in human ears using both the Zwislocki acoustic bridge and an acoustic bridge which he developed. He found a threshold of approximately 60 db SL with his acoustic bridge and about 68 db SL with the Zwislocki bridge. Dallos³³ also with the Zwislocki acoustic bridge reported a mean threshold of 72 db SL when white noise was used to stimulate the reflex.

The experiments of Lilly⁶ and Dallos,³³ using a white noise stimulus, display somewhat lower reflex thresholds than other experiments using pure tone stimuli (Jepsen;^{18,33} Metz³¹). Metz² noticed that the reflex was more easily elicited by noise than by pure tones, but he presented no data to confirm this.

It should be noted that only one paper, reporting on three subjects, has been published comparing the thresholds of the stapedius reflex for noise and pure tones in the same subjects. Kjupestrand, et al,³⁴ found that the impedance threshold to white noise was lower than to pure tones in all three subjects tested. The data are highly variable (the three thresholds for white noise vary from 56 to 78 db SL) and no quantitative conclusions can be drawn. They also determined the threshold of the stapedius reflex for 250, 1000, 2000 and 4000 c/s in 11 normal ears; the values lie between 87.3 and 91.2 db SL. These thresholds are somewhat higher than those found by Jepsen,³ but are lower than those published by Weiss et al.³²

Moller³⁵ has found that the threshold of the human stapedius reflex is slightly lower if the impedance is monitored in the ear that is stimulated rather than in the contralateral ear, as is the usual practice. He also notes that the reflex threshold is three db lower if

the stimulus is presented binaurally. Moller³⁶ has suggested that the sensitivity of the stapedius reflex should be measured in terms of percent of impedance change rather than threshold; although this method may have some advantages, it would be difficult to compare results across methods.

In summary, it is noted that considerable variability can be found in the literature dealing with the threshold of the stapedius reflex in man. No systematic study of the differential response to noise and pure tone stimuli has been published; data on the response to narrow band noise are not available. Studies comparing the stability of the stapedius reflex threshold for the various pure tone stimuli are not in evidence; nor has the stability of the thresholds for noise and pure tone stimuli been compared. Our knowledge of this parameter of the stapedius reflex is not much greater than it was in 1952 when Metz found that the threshold of the acoustic stapedius reflex was in the range 70 to 90 db SL.

e. Latency of the Stapedius Reflex.

Lorente de No,^{13,37} Metz,³⁸ and Okamoto, Sato, and Kerikae,³⁹ have all demonstrated that the latency is dependent upon the intensity of the stimulus; the greater the intensity, the shorter the latency.

Because of differences inherent in the many methods used to study latency, it is difficult to compare results (Wersall¹⁶). It is generally known that the latency of the stapedius is shorter than that of the tensor tympani (Wever and Lawrence¹).

Perlman and Case⁴⁰ found the latency of the stapedius reflex to be about 10 ms in humans; they recorded action potentials from the stapedius in patients with large eardrum perforations. Metz³⁸ used impedance change recordings and found that the latency of the stapedius reflex in human subjects varied from 35 to 150 ms depending on the intensity of the (1-ks/s) stimulus. Moller⁴¹ found latencies in human ears varying from 25 to 32 ms when an intense acoustic stimulus was presented.

Eliasson and Gisselsson¹⁵ recorded latencies of 6 ms for the stapedius and 7 ms for the tensor tympani in cats, using an electro-

myographic technique. Okamoto, et al³⁹ measured eardrum movement in cats and found a minimum latency of 7 ms. Galambos and Ruppert⁹ measured changes in the level of the cochlear microphonic to study the reflex activity in cats. Their results show latencies of 10 to 15 ms, depending on the stimulus.

f. Adaptation of the Reflex.

Metz² in his studies on human ears using the impedance method found that the stapedius reflex could be maintained for long intervals before a gradual relaxation set in. This is noted to be an adaptation process because if the stimulus was stopped and then presented again without delay, the reflex reappeared in full strength (Wever and Lawrence¹). Also, Wersell¹⁶ found that if a second tone, of a different frequency, was presented during the process of adaptation, it reactivated the reflex completely.

Two recent experiments in human ears demonstrate that no short-term adaptation or fatigue is present to very intense stimuli. Dallos³³ was able to maintain the stapedius contraction in human ears for two minutes without any indication of a loss of tension; the elicitor was 110 db SPL of white noise. Lilly⁶ did not observe adaptation with high intensity noise stimulation lasting up to 10 minutes.

The difference in adaptation found may be attributable to the spectrum differences in pure tone and noise stimuli. No clarifying data are available at the present time.

B. Concept of Acoustic Impedance.

1. Basic Concepts.

Acoustic impedance is comprised of mass, elasticity, and resistance. Mass refers to the weight of an object; for example, a middle ear filled with a viscous fluid would have a high mass in comparison to the normal ear. The elasticity of the system is usually discussed in terms of compliance and stiffness. A fixation of the incudo-stapedial joint, as seen in advanced otosclerosis, would cause a stiffness; an incudo-stapedial separation would cause the opposite extreme, a grossly compliant system (Feldman⁴²).

The stiffness and mass components of impedance are generally combined into one resultant measure called reactance. The reactance is a negative value when the system is characterized by stiffness and is positive in mass controlled systems. The effect of stiffness is greatest at low frequencies; the effect of mass is greatest at high frequencies (Zwislocki⁴³).

In all systems in which there is movement, there is a certain loss due to friction; for example, an extreme viscosity in the middle ear would produce a strong internal friction when sound waves progress across the ossicles. The frictional contribution to impedance is called resistance.

The actual acoustic impedance is determined by inserting the values for the reactance and resistance into the following formula (Tonndorf⁴⁴):

$$Z^2 (\text{impedance}) = (\text{reactance})^2 + (\text{resistance})^2$$

When an acoustic wave arrives at the tympanic membrane, part of the energy produces a vibration of the drum and is transmitted through the ossicular chain to the inner ear; a portion of the acoustic wave is reflected back into the external auditory meatus (Zwislocki⁴³). The reflected energy from the tympanic membrane is maximal when the middle ear system is stiff (low in elasticity), heavy (high in mass), and viscous (high in friction). A system which is compliant, light and relatively low in friction will have greater efficiency because reflected energy will be minimal (Zwislocki⁴⁵). Because of this variation in resistivity to motion (or impedance) that is associated with the condition of the middle ear, the study of the reflected wave at the tympanic membrane provides knowledge which is of clinical value.

It should be understood that factors which determine impedance, mass-elasticity, and resistance, are the resultant of the anatomical structure of the ear. Some of the most important factors are the compliance and mass of the tympanic membrane, the compliance of the ligaments that hold the ossicular chain in place, the compliance of the incudo-stapedial joint, the mass of the ossi-

cles, the compliance of the cochlear windows, and the input impedance of the cochlear (Zwislocki⁴⁶).

According to Zwislocki,⁴³ it is only necessary to determine the ratio of the reflected and the incident waves in order to measure the acoustic impedance at the tympanic membrane.

2. Effect of the Acoustic Reflex.

Contraction of the stapedius muscle causes a change in tension on the ossicular chain. The resultant increase in stiffness alters the impedance of the middle ear (Metz;² Feldman and Zwislocki;⁴⁷ Lilly and Shepherd;⁴⁸ Dallos;³³ and Moller^{41,49,50,35}). The general finding of the majority of the studies is that contraction of the stapedius muscle causes an increase in reactance and a decrease in resistance; the former is commonly seen in stapedia fixations (e.g., otosclerosis) but the latter is not. It should be noted that the data of Lilly and Shepherd⁴⁸ do not show a notable decrease in the resistance and more closely approximate the absolute impedance values associated with otosclerosis.

According to Feldman and Zwislocki,⁴⁷ the predominant change caused by the stapedius reflex is an increase in the reactive component; this change is in the same direction as otosclerosis but smaller. They also find a smaller, but consistent decrease in resistance; the authors suggest that this can be accounted for by a loosening of the incudo-stapedial joint in addition to the partial fixation of the stapes.

The existence of a measurable change in the resistance and reactance values associated with the contraction of the stapedius muscle is well established, although attempts to measure the size of the change (and in some cases the direction) have indicated some variability (Moller;⁴⁹ Dallos³³). This variability does not hamper the use of the monitoring of impedance to detect the contraction of the stapedius muscle, since one is concerned only with a sudden change in the static impedance regardless of direction.

C. The Acoustic Bridge.

1. The Measurement of Impedance.

There are several ways in which the acoustic impedance at the eardrum can be measured. In 1957 Zwislocki described two psychoacoustic methods which he employed and found to yield comparable results to purely physical methods. The first is based on the measurement of attenuation produced by a perforated earplug. According to Zwislocki⁵¹ when the perforated earplug closes the ear canal a resonator is formed; the resonance frequency is dependent on the acoustic inertance of the perforation, the acoustic compliance of the enclosed volume of air and the impedance at the tympanic membrane. When the impedance of the perforation and the volume of air between the earplug and the eardrum are known, it is possible with some time-consuming calculations to determine acoustic impedance at the eardrum.

The second psychoacoustic method described by Zwislocki is similar to the one described above but uses a binaural loudness balance technique; another difference is that this method uses sound localization (phase balance) to measure the phase shift introduced by the earplug.

Zwislocki⁵¹ notes that the psychoacoustic approach to impedance measurement is too time-consuming and lacks precision.

The use of an impedance tube was described by Zwislocki⁴⁸. In this method the sound produced by an earphone is fed to the ear canal by a narrow tube which is held in place by an earplug; the plug also serves to form an acoustic seal of the canal. An additional tube, which is fitted into the same earplug, is led to a microphone which is used to measure the sound pressure level in the ear canal. A cavity with rigid walls is used to calibrate the system. According to Zwislocki⁴⁸ the acoustic impedance may be determined by comparing the sound pressure generated in the calibration cavity to the sound pressure generated in the ear canal. A correction for the volume of air in the canal is necessary. The calculations that must be used to convert the results of this method to impedance values are extensive.

Moller^{52, 49} used another technique to measure acoustic impedance. He had a probe tube with a microphone and a transducer; the output voltage of the microphone was measured as was the phase angle between the microphone and the transducer. An electrical analog was then used to convert the data into acoustic ohms.

2. The Acoustic Bridge Principle.

A generalized acoustic bridge consists of a two-sided earphone mounted between two tubes, A and B of equal diameter and length. The diaphragm of the earphone separates the two tubes; the two tubes are connected through a Y-tube that bridges the earphone. The top of the Y tube is fed to the examiner's ear; tube A is secured into the subject's ear canal with an earplug; tube B is attached to a variable impedance device. The sound generated by the earphone is of equal amplitude in both directions (tubes A and B), but 180° out of phase. Consequently, if the impedances terminating tubes A and B are equal the reflected waves will also be of equal amplitude and cancel each other out (Tillman, et al⁵³).

The measurement is accomplished by adjusting the variable impedance device until the tone that is generated by the earphone is no longer audible at the top of the Y tube (a null is present). If the volume of the ear canal is determined, an equal volume can be added to the volume of tube B before measurement of the impedance. If this is done, the measurement is direct and no additional calculations are needed (Zwislocki⁴³).

3. Earlier Acoustic Bridges.

The acoustic bridge was invented in 1934 by Schuster; three years later Robinson built a second acoustic bridge. In 1938 Waetzmänn adapted the Schuster bridge for use in human ear measurements (Metz²). The history of the use of impedance measurements on normal and pathological ears begins with the 1946 Metz monograph in which he demonstrated that pathologic changes in the middle ear could be identified by measuring the impedance in the ear canal; he was also able to identify the pres-

ence of an acoustic reflex using his modified Schuster bridge.

The exact construction of the Schuster bridge is discussed in detail by Metz² and Zwislocki⁴⁵. It should be noted that the bridge Metz used had several limiting features. The impedance matching device was a felt disk varied by means of a column of air in back of the disk. In this type of system the reactance and resistance may not be varied independently. The felt disk is subject to changes with time and use, thereby introducing an error factor. The results are not in their final form when read off the bridge and considerable time is consumed in conversion (Zwislocki⁴⁵).

4. Electroacoustic Bridges.

For a variety of reasons, several of which were mentioned above, absolute impedance measurements for middle ear diagnosis met with little clinical acceptance following the Metz² monograph. In addition to those problems already mentioned, difficulties in accurately compensating for ear canal volumes were encountered (Tillman, et al⁵³); the resultant of these problems was, considerable variability in absolute impedance values obtained.

Following the Metz article, a number of electroacoustic impedance bridges were constructed for clinical use; among these are the bridges of Morton and Jones⁵⁴, Moller⁴¹, Terkildsen and Scott Nielsen⁵⁵, and Klockhoff¹⁷.

Most of the clinical research with the electroacoustic bridge provided absolute impedance data which were highly variable and of little diagnostic value. Terkildsen and Scott Nielsen⁵⁵ concluded that measures of absolute impedance may prove to be of little clinical value but that studies of relative impedance (the stapedius reflex) may be useful.

A large number of articles suggesting the clinical value of relative impedance measures were reported using electroacoustic bridges (Jepsen⁵⁶, Thomsen^{57, 58, 59}, Terkildsen and Scott Nielsen⁵⁵, Klockhoff¹⁷).

The several electroacoustic impedance bridges mentioned above were all based on the same principle, although there are some

minor differences. A brief description of the bridge developed by Terkildsen and Scott Nielsen⁵⁵ will be used to exemplify this type of instrument.

The electroacoustic bridge consists of an earphone and a microphone which are connected to the external auditory meatus by two narrow tubes. The tubes are held in place by an earplug which is encased in an inflatable rubber cuff; after the earplug is in place the cuff is inflated, giving an airtight seal of the canal. The tube from the earphone carries a 220-c/s test tone to the canal. The microphone is used as a sound probe; this signal is counter-balanced to zero by means of current from a 220-c/s sound generator. The degree of counter-balancing obtained is read on a vacuum tube voltmeter. This bridge does not provide individual reactance and resistance measures; only the total acoustic impedance is measured.

A newer version of this bridge is commercially available from Madsen Electronics (Electroacoustic Impedance Meter Z0 70); according to the manufacturer, this model also measures the volume of the ear canal automatically.

D. Clinical Use of Impedance.

1. Absolute Impedance Measures.

The first paper dealing with the use of acoustic impedance measures for differential diagnosis of middle ear pathology was presented by Metz². For a number of reasons, some of which were discussed earlier, the methods suggested by Metz gained little acceptance as a clinical tool. Because they found absolute impedance measures to be unstable, a number of workers investigated the use of the stapedius reflex in clinical diagnosis (Jepsen⁵⁶, Thomsen^{57, 58, 59}, Terkildsen and Scott Nielsen⁵⁵, Klockhoff¹⁷). These studies were all done with electroacoustic impedance bridges that were basically similar to one another. In their investigation of the stapedius reflex, Terkildsen and Scott Nielsen⁵⁵, using an electroacoustic bridge, reported that absolute impedance measures were insufficiently reliable for any clinical inference.

Mundie⁶⁰, working with guinea pigs, suggested that the impedance is not stable; he believes that momentary changes in the impedance reflect a readjustment of the conductive mechanism. No evidence to support this in human subjects is available.

The development of the Zwislocki acoustic bridge has stimulated further research into the clinical use of absolute impedance measures (Feldman^{61, 42, 62}, Feldman and Zwislocki⁴⁷, Zwislocki⁴⁵, Zwislocki and Feldman⁶³). These articles indicate that evaluation of the parameters of compliance and resistance provides significant information for the diagnosis of middle ear pathologies such as otosclerosis and ossicular discontinuity.

Feldman⁶¹ compared 40 normal and 55 otosclerotic ears and found that the pathological ears had consistently smaller compliance values (increase in reactance) than the normal ears. There is some overlap in the results, but this is minimal and may be attributable to incipient pathology; impedance changes have been observed in ears before the pathology was sufficient to alter the threshold. The otosclerotic ears also displayed greater resistance values in the lower frequencies; this difference was most marked at 125 and 250 c/s.

Feldman⁴² showed that fluid in the tympanic cavity will result in changes in the impedance that are in the same direction as otosclerosis; however, such conditions as serous otitis media will produce even higher impedance than otosclerosis.

Ossicular discontinuity has been shown to produce changes in acoustic impedance that are opposite to otosclerosis (Feldman⁶¹). In these ears the compliance value is quite large (indicating low reactance); the resistance is also somewhat lower than that found in the normal ear.

Feldman⁶¹ points out the value of acoustic impedance measures after stapes surgery to detect the condition of the prosthesis. The compliance is usually somewhat larger than normal with a prosthesis and will be considerably larger if the prosthesis has become dislodged.

2. Clinical Use of the Stapedius Reflex.

Metz² noticed that the stapedius reflex appeared to be absent in ears with a conductive impairment. Terkildsen and Scott Nielsen⁵⁵ indicated that a relatively normal ear is a prerequisite for the acoustic stapedius reflex. Klockhoff¹⁷ presented a number of cases of mild conductive impairment; he found the stapedius reflex to be absent in all of these cases and concluded that the presence or absence of the stapedius reflex is the equivalent of the presence or absence of any conductive component. Feldman¹⁹ also demonstrated the absence of the stapedius reflex in ears having middle ear pathology.

Although no definitive studies on the minimal amount of middle ear disturbance necessary to cause a cessation of the stapedius reflex are available, it seems reasonable to conclude that the stapedius reflex is present only in substantially normal middle ears. The clinical importance of this fact is obvious.

3. Recruitment.

Metz³¹ first demonstrated the use of the stapedius reflex as an indicator of recruitment. He found that the reflex was activated at unexpectedly low levels in ears showing recruitment on the alternate binaural loudness balance test. Additional data on the use of this technique have been presented by Thomsen⁵⁷ and Ewertsen, et al⁶⁴. Their results are somewhat sporadic but confirm the potential of the technique.

When the stapedius reflex threshold is used as a test of recruitment, one need not be concerned with such variables as severity of loss or reliability of the patient's judgments. Furthermore, unilateral and bilateral losses can be evaluated with equal ease.

This technique appears to have sufficient merit to warrant further study to determine which stimuli are most useful in demonstrating recruitment. In order to qualify this measure, data must be collected on the stability and reliability of the stapedius reflex threshold to various stimuli in both normal and recruiting ears.

4. Non-organic Hearing Loss.

The use of the stapedius reflex to identify non-organic hearing loss was suggested by Jepsen⁵⁶. Lamb and Peterson⁶⁵ also used this method to detect non-organic hearing loss.

Although data for standardization of the clinical use of the acoustic bridge are still lacking in many areas, the results now available are encouraging. The technique appears to be relatively easy to use, reliable, efficient, and independent of patient judgment.

E. Purpose of Research.

The aims of this study were to: (1) determine the thresholds of the acoustic stapedius reflex for pure tone stimuli in normal human ears using the Zwislocki acoustic bridge, (2) determine the thresholds of the acoustic stapedius reflex for white noise and several narrow-band noise stimuli in normal human ears. This would provide quantitative information on the sensitivity of the reflex differentially to pure tone and noise stimuli, (3) determine the variability and test-retest reliability of the acoustic stapedius reflex thresholds for each of the stimuli employed. The study of the threshold stability and the ease of reflex elicitation associated with each of the stimuli in normal ears should provide guidelines for the selection of stimuli for further investigations of recruitment with the acoustic bridge.

II. PROCEDURE

A. Subjects.

Subjects were 30 normal-hearing young sailors and graduate students; the criterion accepted for normal hearing for this study was thresholds of db or better (ISO⁶⁶), at 250-4000 c/s. All subjects had essentially cerumen-free external auditory canals, intact tympanic membrane and no significant history of ear pathology.

B. The Zwislocki Acoustic Bridge.

1. Description.

The acoustic bridge developed by Zwislocki⁴⁵, and manufactured by the Grason-

Stadler Co., allows direct measurement of impedance components at the eardrum. Cavity V-1 (see Fig. 1) can be adjusted to match the volume of the ear canal being tested; with the volume of the canal added between the end of the B tube and the variable impedance matching device, the effect of the air column in the external meatus is compensated for (Zwislocki⁴⁵).

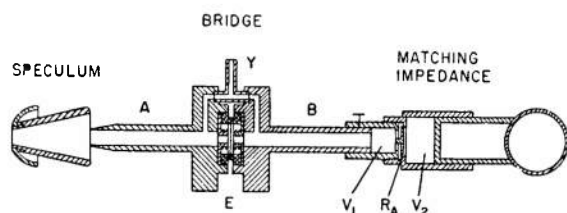


Fig. 1: Schematic diagram of the Zwislocki acoustic bridge.

The A tube of the Zwislocki bridge is machined to fit flush into a special otic speculum; the speculum has three sizes of adjustable plastic tips. The user must select the proper size tip to insure an air-tight seal of the external auditory meatus. The speculum is then inserted into the test ear and the canal is filled with alcohol to the bottom tip of the speculum. This is accomplished with a calibrated 2cc syringe; the amount of injected alcohol is equal to the volume of the ear canal. The alcohol is then removed and tube A of the bridge is inserted into the speculum, after adjusting V-1 to the proper volume.

The variable impedance device at the end of tube B has two independent controls: resistance (R) and compliance (V-2). According to Zwislocki⁴⁵, compliance is measured rather than reactance because compliance is less frequency dependent than reactance, and by using compliance it is possible to make the bridge calibration independent of frequency.

No calibration charts are necessary because the values are indicated directly on the controls; the resistance is measured in ohms, the compliance in cubic centimeters.

The symmetrical earphone (E) is connected to a sound source, such as an audiometer; the sound source generates a test tone (or probe tone) of any frequency between 125 and 1500 c/s, which are the effective limits of the bridge. The probe tone is monitored by the examiner through a stethoscope which is attached to the top of the Y tube (Y).

The compliance control (V-2) is a small piston; the resistance control (R) is a ring around the bridge which is rotated to vary resistance.

The examiner works the two impedance controls back and forth until a null is obtained in the stethoscope (the principle of this has been explained earlier). The compliance and resistance values for that frequency (the probe tone frequency) are now read directly from the bridge. The same procedure can then be repeated for other frequencies within the useful range of the bridge.

It is absolutely necessary to point the tip of the bridge at the eardrum rather than towards the canal wall during all measurements. The examiner should move the bridge as little as possible during the measurement.

All parts of the Zwislocki bridge are machined from metal, eliminating materials such as felt, thereby increasing the stability of calibration (Zwislocki⁴⁵).

2. Visual Display of the Probe Tone.

The monitoring stethoscope can be removed and in its place a microphone can be coupled to the bridge. The output of the microphone can then be led to a suitable electronic apparatus (voltmeter, graphic level recorder, oscilloscope, etc.); the probe tone level can then be monitored visually and permanent records can be obtained in a manner similar to the recording technique used by Klockhoff¹⁷ with an electroacoustic bridge.

3. Measurement of the Stapedius Reflex.

The stapedius reflex can be detected with the Zwislocki acoustic bridge by introducing a sufficiently intense acoustic stimulus into the contralateral ear after the bridge has been balanced (a null is present). The stapedius contraction changes the impedance of the system, causing an unbalancing of the bridge (probe tone returns).

It should be noted that if one is interested only in detecting the acoustic reflex with the Zwislocki bridge it is not necessary to measure the ear canal volume; this measurement is needed only for calibration of the resistance and compliance parameters, which are of no concern in relative impedance measures.

4. Reliability of Measurements.

Three investigations of the reliability of impedance measurements obtained with the Zwislocki bridge have been reported in the literature. Tillman, et al⁵³, presented data on 10 male adult subjects collected by each of the three experimenters; each subject was tested twice by each experimenter, thus, data are provided for both intra- inter-experimenter reliability. They also present data on the reliability of ear canal volume measurements.

Nixon and Glorig⁶⁷ published on the reliability of measures with the Zwislocki bridge obtained by one investigator over four trials; 13 young normal adults served as subjects.

Feldman⁶² presented reliability data on both ear canal measurements and impedance measurements. For this study one investigator collected the measurements on 33 subjects with normal hearing; an additional 24 were used for the data on ear canal volume.

(a) Compliance.

All three articles indicate a relatively high test-retest reliability for the measurement of compliance (the reactance component of impedance) up to 750 c/s; data at 1000 and 1500 are somewhat less stable and more dispersed due to the positive reactance of the system at these frequencies. The resultant of this is often no detectible change

in the monitored signal with relatively gross movements of the compliance adjustment.

Feldman⁶² presents test-retest reliability coefficients ranging from .71 to .95 for compliance values at 125, 250, 500, 750, 1000, and 1500 c/s. Nixon and Glorig⁶⁷ tested 200, 400, 600, 800, and 1000 c/s and obtained reliability coefficients in the range of .49 to .97; 7 of 10 coefficients presented exceed .85 and two of the three that did not exceed .85 were measurements taken at 1000 c/s.

Tillman, et al⁵³ present reliability data for 250, 500, 750, 1000, and 1500 c/s for three experimenters. Reliability coefficients for compliance range from .73 to .92 for 250 through 750 c/s; significantly lower values are seen at 1 kc/s. It is important to note that inter-scorer reliability was also high for compliance (.75 to .99 for 250-750 c/s).

(b) Resistance.

The data on all three studies indicate that the resistance values obtained on the Zwislocki bridge are less stable than the compliance values and dispersed over a greater range. Feldman⁶² suggests that resistance measures are therefore of less diagnostic value than compliance measures. Resistance, in contrast to compliance, becomes more stable as the frequency becomes higher; at higher frequencies, such as 1000 and 1500 c/s, small movements of the resistance adjustment cause critical changes in the probe tone level, whereas grosser movements of the compliance slide have little effect.

Feldman⁶² found test-retest correlations for resistance ranging from .53 at 125 Hz to .77 at 1500 c/s.

Nixon and Glorig's data⁶⁷ also show a reduction in the size of the reliability coefficients for resistance in comparison to compliance (except for 1000 c/s), although their values are somewhat higher than Feldman's. The range of the reliability coefficients is .78 to .92 for 200-1000 c/s.

Tillman, et al⁵³ obtained poor reliability data for resistance measures. The reliability coefficients range from —.18 to .55; inter-scorer values were lower. It should be noted that these values were obtained using a rank-

order correlation technique which is not appropriate for these data; the absolute difference between test and retest values was, at maximum, 4.4 (arbitrary) units on a scale of 60 units. Despite the data, they concluded that resistance measurements with the Zwislocki bridge are reliable; this conclusion agrees with the data and general conclusion of the two other studies.

(c) Ear Canal Measurements.

Both Feldman⁶² and Nixon and Glorig⁶⁷ report highly positive test-retest correlation coefficients for ear canal volume measurements. The former reports reliability coefficients of .96 for one series and .99 for another; the latter report .95 for one series and .93 for another. Tillman, et al⁵³ present reliability coefficients of .84, .58, and .58 for each of the three experimenters. It should be noted that these authors admit to very limited practice with the bridge before the study. The accurate measurement of an ear canal volume is an absolute prerequisite to obtaining valid impedance measurements with the Zwislocki bridge; therefore, the data presented by Tillman, et al⁵³ must be interpreted in the light of their comparatively poor intra-experimenter reliability. The inter-experimenter results for ear canal measurements that are presented in their study range from .002 to .77. Again it should be noted that these results were obtained by the rank order correlation technique and may be somewhat artificially lowered by the nature of the statistic.

The mean canal volume reported by Nixon and Glorig⁶⁷ of .80 cc is somewhat larger than the mean of .56 cc obtained by Feldman.⁶² This difference is related to the depth of insertion of the speculum and is unimportant as long as the insertion depth is held constant while using the bridge; the volume of the canal is compensated for before beginning the impedance measurements with the Zwislocki bridge. However, it should be noted that the weight of the bridge has a tendency to push the speculum in deeper as the bridge is used, reducing the volume of the canal beyond the speculum; a deeper initial insertion of the speculum would tend to minimize this error factor.

(d) Conclusions.

The use of the Zwislocki bridge to obtain absolute acoustic impedance measurements appears to be a reliable technique; results appear somewhat more reliable for the reactance (compliance) component of impedance than for the resistance component.

It should be noted that the sample sizes in both Nixon and Glorig⁶⁷ and Tillman, Dallos, and Kuruvella⁵³ were limited.

A crucial factor in obtaining reliable results with the bridge is the auditory threshold of the examiner. The more acute the examiner's hearing, the longer he will be able to follow the probe tone and the more precise a null he will obtain. The use of visual monitoring eliminates this important variable.

Feldman⁶² notes a possible error introduced into any impedance study using "normal" ears: the existence of incipient pathology may well affect impedance measures before it can be observed either otoscopically or audiologically.

At the present time there is no study available dealing with the reliability of the Zwislocki bridge for the measurement of the stapedius reflex.

C. Other Apparatus and Method.

All data collection and threshold determinations were made in a large sound-treated and isolated room with an ambient noise level of 32 db. With all apparatus running, the level reading increased to 36-37 db at S's head.

Six stimuli were used: (1) white noise, (2-3) narrow-band noise centered at 2 and 4 kc/s; (4-6) pure tones at 2, 4, 0.5 kc/s. The stimuli were always presented in the above sequence.

The stimuli were tape recorded (see Fig. 2). Channel I of the tape recorder received the output of a third-octave narrow band masking generator or oscillator (frequency of the oscillator was set with a meter), through an attenuator and switch; the VU meter on the tape recorder read zero with the attenuator set at zero db. The switch and timer were set so that the stimulus was on

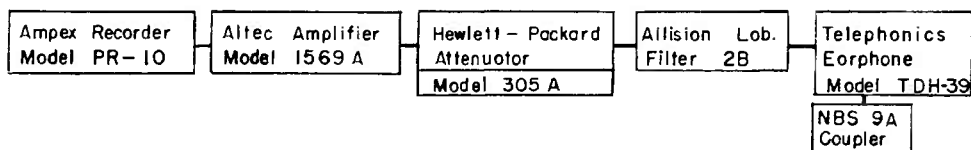


Fig. 3: Block diagram of the stimulus delivery system.

specially built apparatus which was bolted to the examination table. The bridge was inserted in the subject's right ear and locked into place with the bridge holder.

Before the experimental session proper, a subject's hearing was screened at 10 db

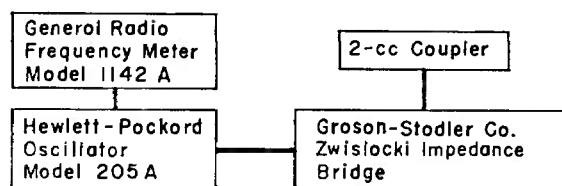


Fig. 4: Block diagram of the probe tone generation equipment.

(ISO⁶⁶) at 250, 500, 1000, 2000, and 4000 c/s, and thresholds in 2-db steps taken (Carhart and Jerger⁶⁵) for the six test stimuli for the left ear, using an ADC pure-tone audiometer and a Beltone type NB 101 noise generator.

The only instructions given to the subject were to lie as still as possible and not to talk unless absolutely necessary. Any sudden movements by the subject were noted on the paper tape in the corresponding place by the examiner. The subject was also told that he would hear several series of sound bursts in his left ear.

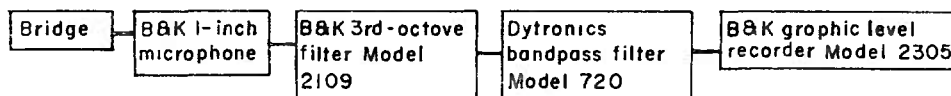
After the subject was placed in the proper position on the examining table, a proper size tip for the ear speculum was selected and coated with petroleum jelly; the choice of a

tip that effectively seals the external canal is essential. The bridge was then inserted in the subject's right ear and fixed in place with the mechanical bridge holder.

The bridge was balanced using the db meter on the spectrometer; finer adjustments were made by watching the pen of the graphic level recorder. When the point of minimal intensity of the probe tone had been reached, the first stimulus sequence was presented at such a level that the terminal stimulus was 110 db SPL. If a response was seen in the middle of the latter portion of the run, or if there was no response, the same series was repeated; if a response was seen in the very early portion of the series, the second run was presented with an additional 10 db of attenuation (terminal stimulus at 100 db). If the results of either of the first two series were unclear, a third series was presented. This procedure was repeated for all six stimuli. For the last nine subjects, a third run of the white noise stimulus was presented regardless of the results of the first two runs. The first scored run of any stimulus will here be called the "test" run; the second, "retest."

The intensity of the probe tone was carefully monitored throughout the experiment; it was frequently necessary to readjust the bridge between series to maintain a sharp null.

During the course of the experiment the investigator monitored the 100 c/s tone and recorded its occurrence with the manual event



Note: B&K= Bruel and Kjaer Co.

Fig. 5: Block diagram of the data recording system.

marker. This allowed the scorer to determine the intensity at which the first response was recorded. This system, however, did not allow for measurement of the latency of response.

The paper record of responses was marked in a code so that the absolute level of the stimuli could not be determined by scorers other than the investigator. A sample of five records was randomly selected and scored by two additional scorers, both professional audiologists.

Figures 6-8 show the responses of the stapedius muscle to various stimuli. The pip at the top of the recording indicate the onset of the stimulus.

All scorers adhered to the following six guidelines in scoring a record:

- (1) In order to be accepted as a response, a peak must be part of a continuous series or chain of responses.
- (2) Responses must be associated in time with the stimulus onset.
- (3) Responses should be examined from the end of the series towards the begin-

ning to take advantage of the increased clarity of the responses to higher intensity levels.

(4) The shape of a possible response in that series, in comparison with clearer responses in that series, may be used to aid in decision-making.

(5) The first two readable series will be used to determine the test and retest values for that record.

(6) If the initial point of response is unclear, a conservative point of view is to be adopted.

The statistical analyses employed in this study are all common-place techniques; the formulas were taken from Dixon and Massey⁶⁹ and Ferguson,⁷⁰ but are available in any standard text on the subject.

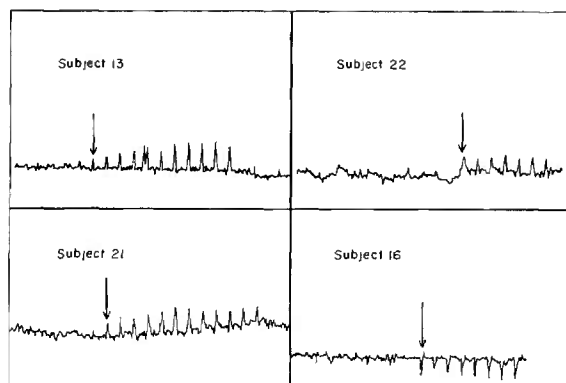


Fig. 6: Stapedius response recording to various stimuli at the normal recording speed.

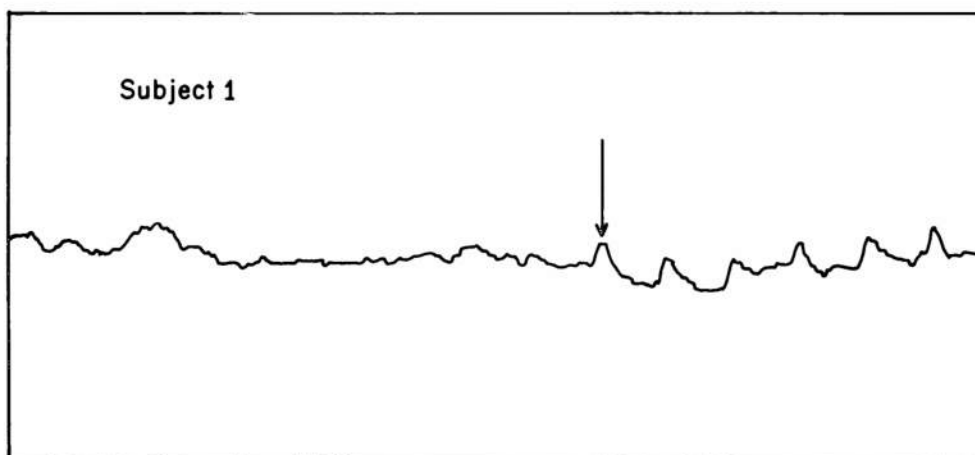


Fig. 7: Stapedius response recordings taken at the fast speed.

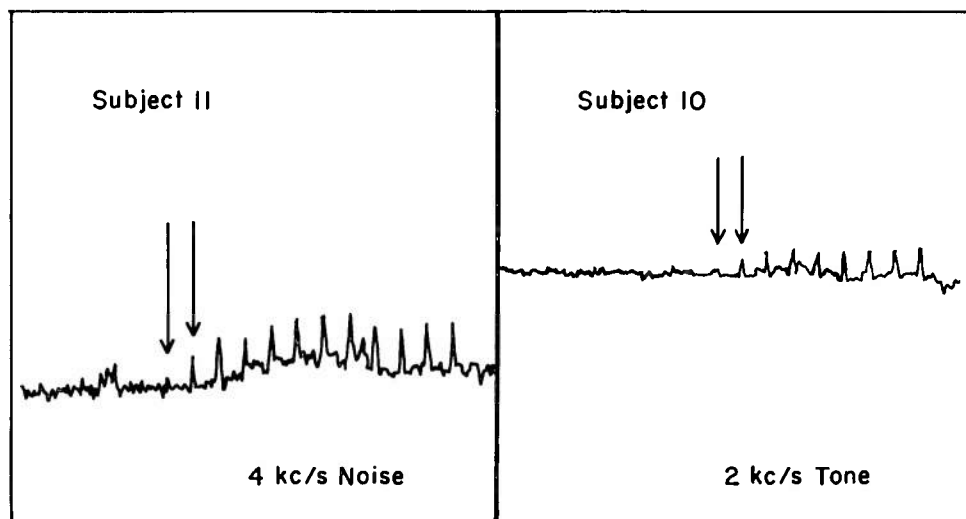


Fig. 8: Stapedius response recording showing a questionable first response.

III. RESULTS

Table I gives the raw and summarized data for the six stimuli. Responses were not elicited from all subjects to all stimuli, so the "Number of subjects" column in Table I is not the same for each stimulus. All 30 subjects tested responded to the white noise and 4 ks/s narrow band noise, but responses to the 250-c/s stimulus were seen in only four subjects; 250 c/s is not further considered here.

The thresholds for all three noise stimuli are (61.6, 61.6 and 62.1 db SL). The thresholds to pure tone stimuli were at a notably higher level than those to the noise stimuli: that to 2-kc/s pure tone was 81.6, and to a 4-kc/s pure tone was 81.1 db SL. It thus required about 20 db of additional stimulation to obtain a response to pure tones.

Table I shows that in all but one case the retest threshold was lower by up to 1.3 db than the initial threshold.

TABLE 1. MEAN STAPEDIUS REFLEX THRESHOLDS (IN DB SL) AND ASSOCIATED STANDARD DEVIATIONS FOR BOTH THE TEST AND RETEST CONDITIONS FOR THE SIX EXPERIMENTAL STIMULI.

	white noise	narrow band 2kc/s	narrow band 4kc/s	2k c/s pure tone	4k c/s pure tone	250 kc/s pure tone
Number of Subjects	30	29	30	29	15	4
Mean (test)	61.6	61.6	62.1	81.6	81.1	73.5
Standard Deviation	4.4	4.7	5.6	9.1	8.8	2.6
Mean (retest)	60.5	60.3	61.6	80.7	80.9	73.5
Standard Deviation	5.24	6.24	5.55	8.51	8.52	2.96

Subject No.	White Noise			N-B 2kc/s			N-B 4kc/s			2k c/s			4k c/s			250 kc/s		
	SPL	TH	SL	SPL	TH	SL	SPL	TH	SL	SPL	TH	SL	SPL	TH	SL	SPL	TH	SL
1	84	25	53	90	22	68	94	22	76	90	2	88	86	5	81	NR	23	
1 RT	86		61	88		66	88		66	86		84	84		89	NR		
2	78	20	58	60	16	64	86	20	66	NR	3	--	NR	-4		NR	27	
2 RT	80		60	82		66	82		62	NR		--	NR			NR		
3	86	22	64	86	22	64	94	30	64	88	1	87	NR	4		98	29	69
3 RT	86		64	82		60	92		62	90		84	NR			98		63
4	92	34	58	98	32	66	98	30	68	98	1	39	NR	12		NR	23	
4 RT	96		62	96		64	92		64	100		91	NR			NR		
5	100	28	72	88	22	66	94	22	77	92	17	75	NR	0		NR	28	
5 RT	98		70	88		66	92		72	92		75	NR			NR		
6	76	20	56	74	16	58	80	26	56	84	2	82	NR	4		NR	23	
6 RT	72		52	74		58	80		56	78		78	NR			NR		
7	88	30	58	NR	28	--	90	28	52	98	9	89	94	7	97	NR	33	
7 RT	84		54	NR		--	96		68	100		91	92		85	NR		
8	92	40	62	94	33	61	40	30	55	96	10	86	NR	20		106	31	75
8 RT	94		62	92		59	86		51	92		82	NR			104		73
9	90	30	60	94	28	66	92	20	66	84	6	78	NR	4		102	27	75
9 RT	88		58	96		68	94		68	86		80	NR			102		75
10	96	30	66	92	28	64	90	30	60	98	4	94	NR	2		NR	28	
10 RT	98		68	86		58	94		64	96		92	NR			NR		
11	92	26	66	86	21	65	86	21	65	92	-3	95	94	-1	95	NR	28	
11 RT	90		64	88		67	82		61	84		87	90		91	NR		
12	98	23	65	86	28	58	94	30	64	90	2	88	98	1	97	NR	23	
12 RT	96		63	90		62	94		64	92		90	100		98	NR		
13	92	25	67	82	22	60	84	23	61	96	12	84	100	15	85	NR	33	
13 RT	90		65	82		60	84		61	94		82	98		85	NR		
14	92	25	67	88	21	67	92	21	61	98	12	86	104	10	84	NR	29	
14 RT	94		69	90		69	94		63	94		82	102		82	NR		
15	94	28	66	80	22	58	80	24	56	82	2	80	NR	4		NR	33	
15 RT	88		60	76		54	86		62	82		80	NR			NR		
16	84	22	62	86	20	66	98	24	74	94	-3	87	NR	-6		NR	23	
16 RT	88		66	82		62	94		70	82		85	NR			NR		
17	88	33	55	96	30	66	88	31	57	100	6	94	96	15	81	NR	33	
17 RT	84		51	94		64	92		61	96		90	96		81	NR		
18	92	28	64	84	24	50	84	24	60	92	6	86	NR	7		NR	31	
18 RT	90		62	84		50	82		64	90		84	NR			NR		
19	84	30	54	80	26	54	80	26	54	74	15	59	82	16	64	NR	35	
19 RT	88		58	78		52	78		52	74		59	78		60	NR		
20	86	24	62	84	22	62	80	22	58	80	10	70	NR	14		NR	33	
20 RT	82		58	80		58	78		56	74		64	NR			NR		
21	72	18	54	66	16	50	70	16	54	72	8	64	76	12	64	NR	31	
21 RT	70		52	68		52	68		52	74		66	80		68	NR		
22	78	16	62	74	14	60	68	14	54	70	2	68	80	2	78	NR	20	
22 RT	70		54	72		58	66		52	74		72	82		80	NR		
23	90	20	60	78	20	58	78	20	58	82	4	78	NR	6		NR	28	
23 RT	78		58	78		58	70		58	80		76	NR			NR		
24	86	30	58	82	26	56	84	27	57	80	12	68	90	14	76	NR	33	
24 RT	90		60	82		56	82		55	86		74	88		74	NR		
25	86	24	64	80	20	60	80	21	61	80	3	77	84	5	79	NR	31	
25 RT	88		66	76		56	82		61	84		81	84		79	NR		
26	84	26	58	86	22	64	88	26	62	90	10	80	90	12	78	106	31	75
26 RT	84		58	82		60	86		60	88		78	92		80	108		77
27	88	24	64	80	18	62	84	20	64	96	12	84	96	12	84	NR	27	
27 RT	84		60	80		62	80		60	96		84	92		80	NR		
28	82	18	64	80	14	66	84	16	68	94	8	86	92	8	84	NR	31	
28 RT	84		66	78		64	84		68	96		88	88		80	NR		
29	96	28	68	92	22	70	92	24	68	102	10	92	NR	10		NR	35	
29 RT	98		70	86		64	94		70	98		88	NR			NR		
30	76	20	56	80	16	54	86	20	66	80	8	72	NR	6		NR	28	
30 RT	74		54	76		60	84		64	76		68	NR			NR		

Table II shows the test-retest r,s ; all significant at the .01 level using a two-tail test. The coefficient is notably lower for white noise and 2-kc/s narrow band noise.

Table II also shows that the mean test-retest differences only for the white noise and 2-kc/s narrow-band noise stimuli are significantly different.

TABLE II. PEARSON PRODUCT MOMENT CORRELATION (r) COEFFICIENTS SIGNIFICANCE OF DIFFERENCES, AND HOMOGENEITY OF VARIANCE BETWEEN TEST AND RETEST THRESHOLD VALUES.

	white noise	narrow band 2kc/s	narrow band 4k c/s	2k c/s pure tone	4k c/s pure tone
r	.58	.67	.85	.93	.93
t	2.06	2.73	.93	1.15	.40
Significance level/ 1-tail	.05	.01	NS	NS	NS
F - ratio	1.41	1.74	1.00	1.15	1.07
Significance level/ 1-tail	NS	NS	NS	NS	NS

Table III shows the mean stapedius reflex thresholds for nine subjects decreased about 2 db per run over three consecutive runs, with the white noise stimulus.

Table I shows that the standard deviations for the three noise stimuli (4.42-5.56 db) are relatively homogeneous. The standard deviations for the pure tone stimuli (8.51-9.14) are also relatively close to each other, consistently larger than those associated with the noise stimuli.

Table II shows the variances for the test and retest means. All F values are non-significant, indicating that any change in variance from the test to the retest condition may be attributed to chance factors.

TABLE III. MEAN THRESHOLD VALUES AND TESTS FOR SIGNIFICANT DIFFERENCES FOR THREE CONSECUTIVE DETERMINATIONS OF THE THRESHOLD TO THE WHITE NOISE STIMULUS (N-9)

	1st run	2nd run	3rd run
Mean	60.4	58.4	56.7
t value (1vrs2, 2vrs3)		1.90	2.87
Significance level/ 1 tail		.05	.01

Table IV compares the variances of the various stimuli used. None of the differences among the three noise stimuli reached significance at the .05 level; the difference between the two pure tone stimuli is also non-signifi-

cant. All the comparisons between the variances of the noise and pure tone stimuli are significant at the .01 criterion (using 1 tail values).

The mean scores of three judges obtained by reading all the data records for 5 subjects were 88.39, 88.17, and 88.79 db, differences exceedingly small. It was found that over 90% of both additional scorer's judgments were within 2 db of the experimenter's judgment. The means were based on 46 of the 60 possible responses because 14 of the stimuli showed no response. It should be noted that there was total agreement among the three scorers on all of the stimuli in the no response category. It is therefore concluded that the method used here of response recording allows reliable inter-scorer judgments of the threshold of the stapedius response.

To determine the approximate shape of the distribution of the scores obtained, frequency polygons for each of the stimuli employed were drawn; these may be found in Figs. 9-13. Considering the relatively small sample

TABLE IV. TESTS FOR SIGNIFICANT DIFFERENCES BETWEEN THE VARIANCES OF THE FIVE TEST STIMULI (F RATIO IS TOP NUMBER, 1 TAIL SIGNIFICANCE LEVEL IS BOTTOM NUMBER).

	narrow band 2 kc/s	narrow band 4 kc/s	2-k c/s pure tone	4 k c/s pure tone
white noise	1.14 NS	1.58 NS	4.28 .01	3.98 .01
narrow band 2 kc/s	-	1.39 NS	3.74 .01	3.48 .01
narrow band 4 kc/s	-	-	2.70 .01	2.51 .01
2-k c/s pure tone	-	-	-	1.08 NS

size, the curves are acceptable approximations of normality. All the curves are uni-

TABLE V. MEAN SPL THRESHOLD VALUES ACROSS ALL STIMULI FOR THE EXPERIMENTER AND TWO INDEPENDENT SCORERS (N-5).

	experimenter	scorer MB	scorer HN
mean threshold	88.39	88.17	88.78

modal and only 2-kc/s is skewed to any notable degree. Several of the curves appear to be more peaked than the normal function, indicating a large cluster of scores about the mean.

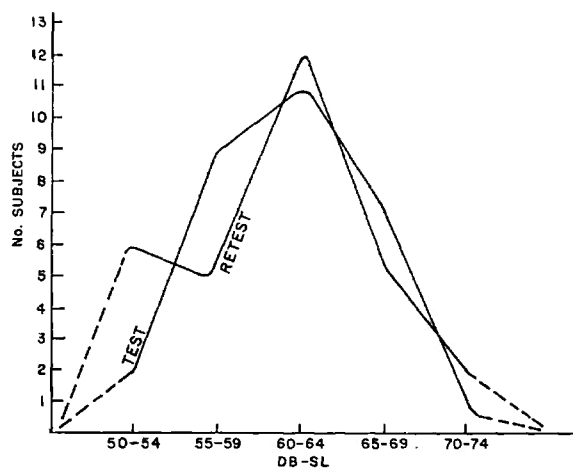


Fig. 9: Distribution of thresholds for white noise.

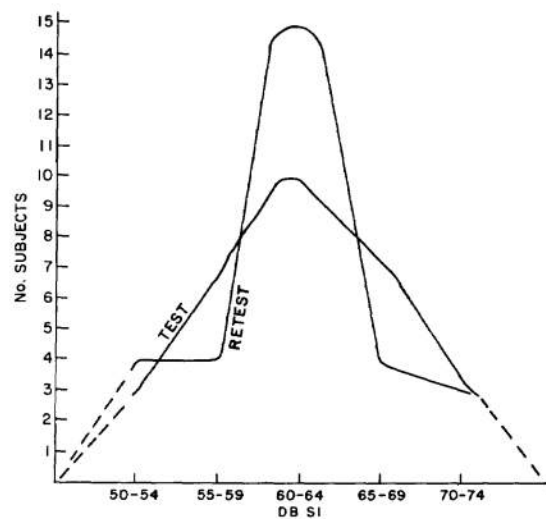


Fig. 11: Distribution of thresholds for 4K Hz narrow-band noise.

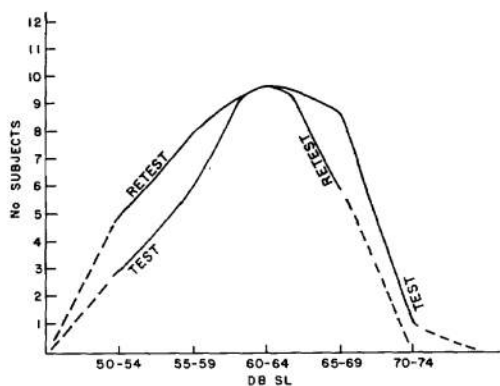


Fig. 10: Distribution of thresholds for 2K Hz narrow-band noise.

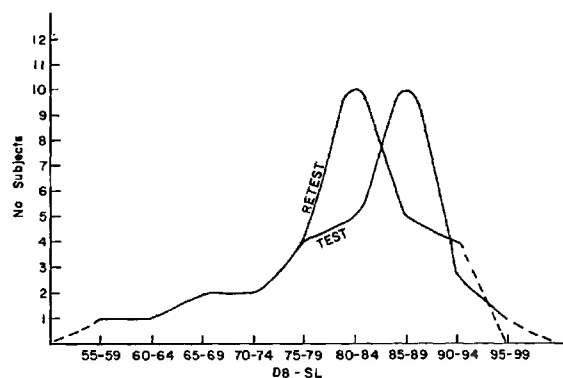


Fig. 12: Distribution of thresholds for 2K Hz pure tones.

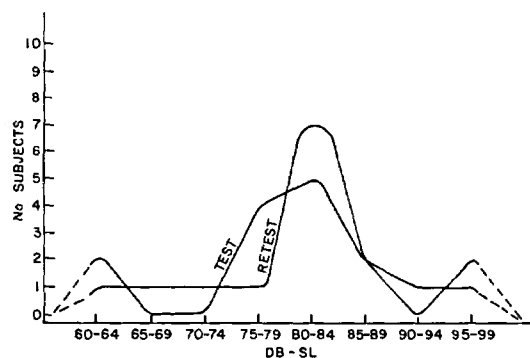


Fig. 13: Distribution of thresholds for 4K Hz pure tones.

IV. DISCUSSION

A. Discussion of the Data.

The stapedius reflex thresholds that were found for the 2 and 4 kc/s pure tone stimuli (81.6 and 81.1 db SL respectively) are in general concurrence with these presented by Metz,² who found pure tone thresholds to lie between 70 and 90 db SL, and Jepsen¹⁸ who found thresholds at approximately 80 db SL for these frequencies. Both of these investigators utilized electro-acoustic impedance bridges to collect their data.

All of these thresholds are in contrast to the data collected by Weiss, et al,³² who used tympanomanometry to record the reflex. Moller,⁷ as was noted earlier, warns that small contractions of the stapedius muscle may not produce measurable changes in the air pressure in the external auditory meatus. The integration of this warning with the knowledge that the strength of the contraction of the stapedius is dependent on the intensity of the elicitor may account for the fact that the thresholds found by Weiss and his associates are approximately 10 db higher than those indicated by the present research. If Moller's suggestion is valid, the investigation of the parameters of the stapedius would best be undertaken with the impedance method due to its superior sensitivity for this work.

Responses in only four of the 30 subjects tested were noted at 250 c/s. Jepsen³ noted difficulty in obtaining responses at 125 and 8000 c/s but was able to obtain responses at 250. He reported a mean threshold for that frequency of 80 db SL; however, the number of subjects responding at that frequency was not reported. This value is in agreement with the threshold of 87.3 db SL reported by Kjupestrand, et al³⁴ for this frequency. It was noted earlier that stimulus recordings were calibrated to allow tones and noise bursts up to 110 db SPL, which would be equal to 85 db re normal human hearing (ISO⁶⁶). It is therefore possible that the intensity of the stimulus at 250 c/s was insufficient to elicit a reflex in the majority of the subjects; the four responses recorded to the 250-c/s stimulus, having a mean of 73.5 db SL, may then represent lower extreme values. It would

seem, however, that a larger number of responses in the area of 80 to 85 db SL should have been recorded if the true mean were located only 5 db above the maximum intensity of stimuli presented.

Responses at the other end of the frequency spectrum utilized were also less consistent; only 15 of the 30 subjects tested responded to the 4-kc/s stimuli. This cannot be attributed to lack of stimulus intensity because 110 db SPL at 4000 c/s is equal to 101 db re normal hearing (ISO⁶⁶). Further study into stapedius response to high and low frequency stimuli is necessary to clarify this matter.

One subject did not respond to the 2-kc/s narrow-band noise stimulus and another did not respond to the 2-kc/s pure tone stimulus; both subjects responded at several other frequencies tested. This occurrence has been noted a number of times in the literature. It is important to note that if a subject's response could be recorded on the test run to a certain stimulus, it was also recorded on the retest run; if no response was recorded to a certain stimulus by a subject during the test run, the retest run always confirmed this finding.

The mean thresholds of the stapedius reflex to all three noise stimuli employed in this study were substantially equal (61.6-62.1 db SL). This 62-db SL value for white noise is in agreement with the value presented by Lilly⁶ using his own acoustic bridge (60 db SL); it is somewhat lower than the 69 db SL threshold to white noise Lilly found with the Zwislocki acoustic bridge. Dallos³³ found the mean response level to white noise to be 72 db SL using the Zwislocki bridge. These reports were based on very limited samples (Lilly, N=5, Dallos, N=6) and cannot be considered to be population estimates; the distribution of thresholds to the white noise stimuli in this study appears to be a satisfactory approximation of the normal distribution.

The reports which noted that the stapedius threshold to noise is lower than to pure tones (Metz,² Jepsen,³ Moller,³⁵ Djupesland, et al³⁴) are confirmed by the data of the present study. The differences between the

thresholds for 2- and 4-kc/s pure tones and those for the various noise stimuli are approximately 20 db. This finding is in sharp contrast to Moller's³⁵ report that there was only a 5-db difference between the stapedius response to noise and a 1450 c/s pure tone; no other comparative study is available.

Simmons²⁹ reported a temporary improvement in the reflex threshold in cats after short exposure to 80-90 db SPL of noise. He studied the reflex threshold using cochlear microphonics and electromyography and noted changes of 7 to 40 db which persisted from a minimum of 5 to a maximum of 40 minutes. He attributes this to a phenomenon called posttetanic potentiation which is thought to be a function of the hyper-excitability of certain brain stem structures following acoustic stimulation.

The phenomenon of auditory sensitization in humans has been reported by Hughes⁷¹ and Hughes and Rosenblith.⁷² Hughes states that the principle that neural systems suffer fatigue effects following stimulation is an over-generalization; sometimes, he continues, the threshold falls instead of rising. He notes in his study of absolute thresholds that the sensitization produced by a pure tone is non-specific; that is, a given tone can sensitize the whole auditory mechanism to a wide range of frequencies. A mean audiometric threshold improvement of 6 db following exposure to a 500 c/s tone at 100 db SPL was reported in three subjects.

It should be noted that the existence of this change in threshold precludes the use of computerized averaging techniques to study the smallest responses of the stapedius muscle, which might not clearly be seen in a single trial.

Because of the significantly smaller variability seen in response to the noise stimuli and their effectiveness as elicitors, it would appear that white noise and narrow-band noise are potentially the best stimuli for use in recruitment testing. Changes due to auditory sensitization which will appear with repeat testing (approximately 2 db) are probably small enough to be ignored for this purpose.

Klockhoff¹⁷ states that, provided that no non-organic hearing loss is present, the stapedius reflex test of recruitment will be unexceptionable. If validated, the method has the advantage of being objective, but one should note that the presence of an incidental conductive impairment would preclude the stimulation of the reflex. In other words, if the reflex is to be used as a conclusive test of the presence or absence of recruitment, the possibility of confounding results due to a conductive pathology must be ruled out. Klockhoff suggests that this can be done with the cutaneous stapedius reflex test; the observation of a cutaneous stapedius response, in the absence of an acoustic stapedius response, would then be interpreted to indicate the absence of recruitment. If no cutaneous stapedius response is observable, this approach to recruitment testing is inapplicable.

It should be noted that a small constant error may have affected the means for the stapedius threshold. In some cases it was difficult to identify the first response of a series because the near-threshold responses were relatively small (see the records in Figure 8). Following the sixth scoring rule (see above) the more conservative (higher) response was chosen. The maximal effect this might have had on the mean threshold values obtained is estimated at 1-2 db.

The system designed to record the stapedius reflex for this study was sufficiently sensitive to allow identification of changes of 1-2 db in the probe tone level. Most near-threshold responses were seen to cause 1.5-3 db changes in the probe tone level; responses to more intensive stimuli caused changes of 11 db (see Figs. 6-7).

It was noted earlier that many initial responses caused changes in the probe tone level of less than 2 db. This would indicate that aural monitoring of the probe tone level to detect the threshold of the stapedius response is inappropriate because such a small change may not be noted by the examiner. This may account for the difference between the threshold for white noise found in this study and the threshold reported by Lilly⁶.

Lilly used aural monitoring of the Zwislöcki bridge and found a threshold of 60 db SL; he may not have been able to perceive the small changes caused by the initial responses.

B. Further Comment on the Stapedius Reflex.

Lilly⁶ reported that the threshold of the stapedius reflex may be dependent on the probe tone frequency used; the mean stapedius reflex threshold for white noise recorded with the Zwislöcki bridge was 69 db SL using the same monitoring frequency as was used in this study (500 c/s), but approximately 59 db SL using a probe tone of 866 c/s (the best tone frequency, according to Lilly). The explanation for this difference is obscure if the intensity of the probe tone was kept safely below the threshold of the reflex, as is obviously necessary; the intensity of the probe tone used by Lilly was not reported.

Reger (in Jepsen³) has measured the threshold shift caused by voluntary contraction of the tympanic muscles; he reports a threshold shift of 30 to 35 db at 125, 250 and 500 c/s. A shift of about 15 db was noted at 1, and no effect was recorded at 2, 4, and 8 kc/s. These shifts are somewhat larger than the 15-db shift reported by Shipley (in Jepsen³) at 250 c/s. Although the exact values are not known, there is sufficient evidence in the literature to conclude that a stapedius contraction has a degrading effect on sound transmission efficiency for the lower frequencies. The results of the present study indicate that the exposure of a normal ear to about 75 db SPL of white noise will cause a stapedius reflex; the effect of the reflex on a pure tone threshold in the contralateral ear appears to be a generally unrecognized error factor in audiometry employing masking. One can only speculate as to how much of the threshold shift commonly accounted for as a central masking effect is due to this factor.

It has been reported in the literature that the stapedius response is absent in the presence of a significant conductive pathology. It has also been demonstrated that an acoustic stapedius response is present in subjects with a severe sensori-neural hearing

loss of cochlear origin. In view of this, it is of clinical importance to note that the impedance method can be used to determine if a secondary conductive pathology exists in an ear which has a severe enough sensori-neural loss to preclude the determination of clinical bone conduction thresholds. The absence of the reflex (acoustic and cutaneous) would be indicative of middle ear pathology.

The use of a visual display apparatus with the Zwislöcki acoustic bridge has several distinct advantages over aural monitoring. With this system, the hearing sensitivity of the examiner is not a confounding variable. Furthermore, permanent records may be obtained for further analyses and cross-validation of scoring methods. The substitution of a data recorder or a storage oscilloscope for the graphic level recorder would allow measurements of the latency of the stapedius response.

It has yet to be determined if this electro-acoustic system would allow for the detection of null points that are as accurate as aural monitoring. The difference if any, based on the experience of this writer, would appear to be small.

C. Suggestions for Further Research.

The results of this study indicate that the mean threshold values for the noise stimuli are approximately $62 \pm$ db SL. It is known that 99% of the normal population will fall within three standard deviations (15 db) of the mean; therefore, it may be stated that 99% of the normal population will have a stapedius reflex threshold to (for example) white noise that is higher than $62 - 15 = 47$ db SL. It would then appear logical that a stapedius reflex threshold of less than 47 db SL should be suspected of being abnormal; this statement is associated with a statistical confidence level of .99. One should note that the only disorder known to cause a lowering of the stapedius reflex threshold is recruitment.

Validity studies for the use of the stapedius reflex test of recruitment are the next logical step in the standardization of the procedure. The initial study should employ patients who demonstrate significant recruitment on the alternate binaural loudness bal-

ance test and the monaural loudness balance test; the comparison of the results of the above recruitment measures with the stapedius reflex test would allow the determination of validity coefficients.

Further study into the identification of partial recruitment should follow. It would appear possible, with the stapedius reflex test, to develop a numerical scale defining the amount of recruitment present. A study of a sample of mildly recruiting ears should be undertaken to determine if these ears are effectively separated from the lower extreme values of the normal population.

The data presented by Jepsen³ indicated that the stapedius reflex threshold decreases with age. The first decrease that can be detected from his graphs appears in the sample of 60-year-old subjects, and is more pronounced in the group of 70-year-old subjects. Assuming that this finding is confirmed, separate norms for these age groups must be established.

Further investigation into the adaptation of the stapedius muscle seems indicated. Although the stapedius is known not to fatigue, it is commonly thought to display adaptation behavior to auditory stimulation; Dallos³³ and Lilly⁶ have suggested that this is not the case with intensive stimulation. A comparison of the muscle's behavior, with respect to this parameter, in response to high intensity noise and pure tone stimuli is needed to clarify the situation.

The delimitation of the minimal pathology which will preclude the elicitation of the stapedius reflex is of clinical importance; if it should be true that any clinical pathology of the middle ear precluded the reflex, the contribution to otological diagnosis and especially otological screening with children would be considerable.

Inasmuch as the introduction of middle ear pathology in measured doses appears to be the most direct method of study, the use of human ears is impractical. Kato noted that he was unable to elicit an acoustic tensor tympani response in monkeys, while contractions of the stapedius were observed. It is possible that study of the effect of pathology

on the middle ears of monkeys may shed some additional knowledge on the problem. The use of fresh cadaver ears for such research may serve as an alternative approach.

Thorough definition of the parameters of the effect of post-tetanic potentiation seems to be overdue. The absolute size of the effect and the relation of the bandwidth and frequency of the stimulus to the size of the effect are essential to complete understanding of the nature of the stapedius reflex.

The relationship between the firing of the tensor tympani and the stapedius muscles and movements of the eardrum has not been clearly defined. The equivalence of inward movement of the drum and a tensor response could be demonstrated with a patient having a sectioned tensor but a normal stapedius; the inability to record inward movements of the drum to acoustic stimuli would be strong evidence for the existence of this relationship. A subject afflicted with Bell's palsy could be used to determine if outward movements of the eardrum to acoustic stimulation could only be accounted for by stapedius contractions; to accept this assumption one must be unable to record outward movement of the eardrum in this subject. Also, on remission of the palsy, outward movements of the eardrum to acoustic stimulation should be recordable.

The comparative sensitivity of tympanometry and the impedance method for measuring stapedius contractions is of importance. The comparison of the reflex thresholds determined by the two methods in subjects with inoperative tensor tympani muscles should provide this information.

V. SUMMARY AND CONCLUSIONS

The threshold of the middle-ear stapedius muscle reflex in 30 normal human subjects was recorded graphically using the Zwislocki acoustic bridge, a microphone, and a sound level recorder. The results indicated that:

1. The reflex thresholds for 2- and 4-kc/s pure tones were approximately 81 db sensation level (SL); for third-octave noise stimuli of the same frequency regions, and for white noise, approximately 62 db SL.

2. The lower mean threshold values for noise stimuli were associated with smaller standard deviations. The reflex threshold had a high test-retest reliability regardless of stimuli employed.

3. Thresholds for white noise and for 2-kc/s narrow-band noise decreased slightly with repeated stimulation. This finding was discussed in a framework of auditory sensitization.

4. The data are reliable and stable enough to recommend an objective impedance test of stapedius muscle activity for several purposes: (a) to explore the protective effect of the reflex against low sounds, (b) to serve as an objective audiometric index in certain cases, (c) to determine the presence of "recruitment" (abnormally rapid growth of loudness in certain ears), a very important symptom in clinical audiology, and (4) to serve as a research tool for intra-aural muscle physiology.

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<p>The threshold sound pressure levels for the middle-ear stapedius muscle reflex in response to white noise (constant spectrum level), and to pure tones and narrow bands of noise in the regions of 2 and 4 kilocycles per second, were studied with the Zwislocki acoustic impedance bridge and an objective recording method. Means and the shape of the distributions were provided. Mean thresholds for noise were as low as 62 decibels above audiometric threshold. Reliability and stability were high. It was concluded that the method could be used for a variety of purposes in audiometry, clinical audiology, and physiological acoustics; and for such purposes this paper provides normative data from 30 normal-hearing young men.</p>			

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